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Research on rolling force model in hot-rolling process of aluminum alloys

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Abstract

On the basis of classic rolling-theory, a rolling force model of AA5052 aluminum alloys during hot rough rolling was investigated. Factors which influenced rolling force in the process including radius of elastic flattened roll, stress state coefficient and deformation resistance were evaluated in detail to establish the model. The rolling force prediction program was developed by means of MATLAB and the comparison between calculations and measured values of the rolling force indicated that the rolling force model has good prediction precision with an error between 5%~7% and it can meet the basic requirements of the actual production site.

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Keywords: aluminum alloy; rolling force; mathematical model; hot rolling; rough rolling process

1. Introduction

Rolling force model is the most important comprehensive one of the mathematical models of rolling process, its setting accuracy directly affecting the roll gap settings, thereby affecting the plate quality, such as thickness precision, flatness, and mechanical properties of the final plate coil ^[1, 2]. Rolling force model used widely so far has been built mainly based on steel rolling ^[3-6]. Compared with steel, aluminum has some characteristics of lower flow stress, larger thermal diffusion coefficient, smaller

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hardness, these features bring about that steel strip hot rolling process model can not be directly applied to the rolling process of aluminum alloy and acted as aluminum strip hot rolling model.

Hiroshi Kimura^[7], acted adjustment of the finishing mill as object, developed the compilation method of mathematic model of computer-controlled hot rolling mill of aluminum. Liu et al.^[8] established a rolling force model of hot rolling of aluminum strip for 2800mm mill based on other researchers' previous study. For whether rough mill or finished one of hot rolling, rolling force calculation is one of the most important tasks of a computer. For these reasons, this paper carried on research of rolling force model of rough rolling process of aluminum alloy, makes analysis in detail the influence of the rolling three factors, the elastic roll flattening radius, the stress state coefficient and deformation resistance, on the rolling force. The mathematical model of rolling force established for rough rolling process, with an error of rolling force prediction controlled at 5% to 7%, meet the requirements of the actual production site on the whole.

Nomenclature

P	rolling force, kN
F	the horizontal projection of the contact area between roll and rolled piece, mm^2
P_m	average unit pressure, MPa
B	average width of rolled piece at rolling deformation zone around, mm
l_c	contact arc length, mm
Δh	pass reduction, mm
Q_p	stress state coefficient; -
K	material deformation resistance of plane deformation, MPa
R_0	initial radius of the roll, mm
R'	flatten roll radius, mm
C	roll flattening factor, known as Hitchcock constant
ν	Poisson's ratio of roll, -
E	elastic modulus of roll, Pa
n_{σ}'	the effect coefficient of outside friction, -
n_{σ}''	the effect coefficient of outside area of deformation, -
n_{σ}'''	the effect coefficient of tension stress on stress state, -
h_m	average thickness of rolled piece, mm
τ	distribution of shear stress, MPa
σ	deformation flow stress, MPa
α	material stress level parameter, $\text{mm}^2 \cdot \text{N}^{-1}$
A	material structure factor, s^{-1}
n	material stress power parameter
Q	surface activation energy of hot deformation material, $\text{kJ} \cdot \text{mol}^{-1}$

R	the gas constant
•	
$\dot{\epsilon}$	rate of deformation, s^{-1}
T	deformation absolute temperature, K, $T = t (^{\circ}C) + 273$

2. Establishing for mathematical model of rolling force

Total rolling pressure, referred to as rolling force, is applied loads needed for metal plastic deformation during ingot passes the roll gap. The value of rolling force entirely depends on unit pressure and its distribution. Formula for calculating the rolling force P can be written as the following:

$$P = F P_m B l_c \quad (1)$$

$$l_c = \sqrt{R' \times \Delta h} \quad (2)$$

where, F is the horizontal projection of the contact area between roll and rolled piece, mm^2 ; P_m average unit pressure, MPa; B average width of rolled piece at rolling deformation zone around, mm; l_c contact arc length, mm; R' flatten roll radius, mm; Δh pass reduction, mm.

The most common methods of calculation of average unit pressure are A. Tselikov (Целиков А.И.) solution^[9] and Sims method^[10]. In general, Tselikov method adopts Karman square cross-section assumption, based on Karman equilibrium differential equations of unit pressure, without considering the presence of adhesion zone during rolling, especially hot rolling. It leads that the friction coefficient of rolling process in the formula is difficult to correctly determine. This method is suitable for calculation of average unit pressure during strip's cold rolling due to the assumptions of the conditions used in derivation, as mentioned above, is not conformed well to one of hot-rolling.

Sims solution is based on the Orowan balance differential equations of unit pressure. Orowan hypothesis, which the most important difference from Karman assumptions is that it does not recognize friction coefficient of the points of contact arc constant, considers that whether presence of slip among rolls and strip depends on the size of the friction force between them. Therefore Sims solution is well suitable for calculation of average unit pressure during strip's hot rolling^[11]. In this paper, Sims solution of the average unit pressure was adopted.

$$P_m = Q_p K \quad (3)$$

where, Q_p is stress state coefficient; K material deformation resistance of plane deformation, MPa.

In summary, the establishment of rolling force model, depends on three factors: R' the elastic flatten roll radius, and Q_p stress state coefficient (model) under plane strain conditions and K deformation resistance of materials (model).

2.1. Flatten roll radius model

As local elastic flatten on the roll surface, generated due to rolling force, makes the contact arc length increase, resulting in rolling force becoming larger^[12], so calculation of rolling force must consider

accurately calculating the effect of roll flattening. Calculation of elastic flatten roll, used simplified formula of Hitchcock-style [2] in general:

$$R' = R_0 \left(1 + \frac{CP}{B\Delta h} \right) \quad (4)$$

where R_0 is initial radius of the roll, R' flatten roll radius, and C roll flattening factor (also known as Hitchcock constant) is calculated as follows:

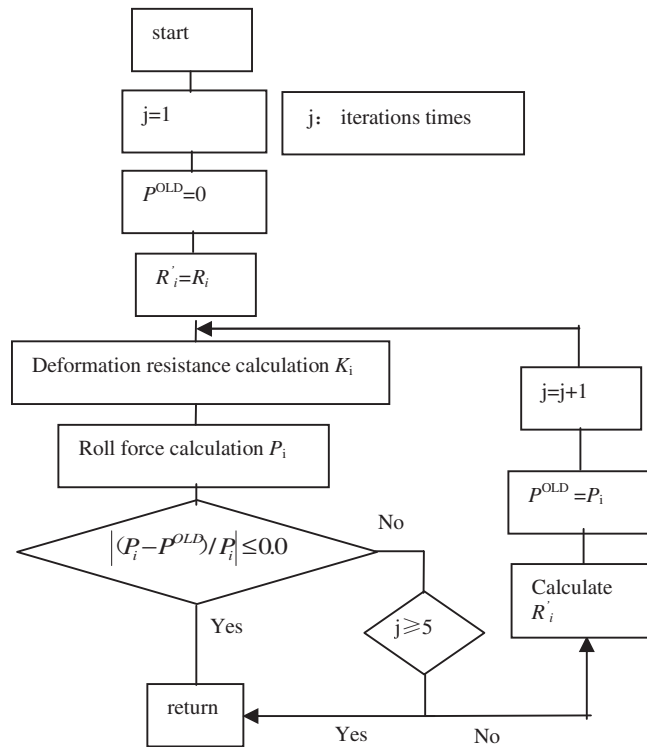


Fig. 1. Flow chart of the calculation of roll flattening radius

$$C = \frac{16(1-\nu^2)}{\pi E}$$

where, ν Poisson's ratio of roll, E elastic modulus of roll, Pa.

But during R' calculation, we need to know the size of rolling force and rolling force is the final need to calculate, that means R' is the implicit function. It can be calculated by iterative method, but need restrictions of number of iterations. Calculation flow chart was shown in Figure 1.

2.2. Stress state factor model

As we all know, the stress state, is very complex, strongly influenced on rolling force, has been the core issue of rolling theory study. There are many factors, including external friction, the outer end geometry and the tension (especially the entrance tension) and other factors, affect the stress state. Stress state coefficient is product of the following three factors [9], that is,

$$Q_p = n'_\sigma n''_\sigma n'''_\sigma \quad (5)$$

thereinto the coefficients n'_σ , n''_σ , n'''_σ , considered the effect of outside friction, outside area of deformation, tension stress on stress state respectively. These factors are complex and mutual influenced, not easy to independently control online via computer, so a simplified regression formula was accustomed to adopt. These, which are more commonly applied among, include S. Shida (Shida Shikeru) formula, Y. Misaka (Misaka Yoshisuke) formula, Colin Terry formula, Saito formula, etc. Saito formula adopted in this article as following formulas (6) and (7). Where, h_m is average thickness of rolled piece. Saito formula assumes that rough rolling process is similar to upsetting one, there being internal friction on the interface of deformation zone, that distribution of shear stress, $\tau = K/2$, on deformation zone changes according to straight line, unit pressure distribution of contact surface is symmetrical^[13].

$$\text{when } \frac{l_c}{h_m} < 1.0, \quad Q_p = \frac{1}{4} \left(\pi + \frac{h_m}{l_c} \right) \quad (6)$$

$$\text{when } \frac{l_c}{h_m} \geq 1.0, \quad Q_p = \frac{1}{4} \left(\pi + \frac{l_c}{h_m} \right) \quad (7)$$

2.3. Deformation resistance model

It was found, from analysis of a large number of process data gathered by means of measured, that deformation resistance is the most active factor in the equation of rolling force^[14] in the rolling process. Research on deformation resistance, mainly using at present a variety of experimental methods, which obtains experimental data of various factors influenced on deformation resistance, explores general rules of deformation resistance among various factors and considers using the corresponding coefficients, which can be obtained via regression from previous experimental data, for expression of the factor value. Deformation flow stress and deformation resistance are expressed usually by hyperbolic sine constitutive equation in metal plastic processing. For almost all soft aluminum alloys, their deformation resistance of thermal deformation is little impacted by deformation extent, almost negligible and regardless of the impact of hardening. Here deformation flow stress model using the form of equation (8):

$$\sigma = \frac{1}{\alpha} \ln \left\{ \left(\frac{\dot{\varepsilon} \exp\left(\frac{Q}{RT}\right)}{A} \right)^{\frac{1}{n}} + \sqrt{\left(\frac{\dot{\varepsilon} \exp\left(\frac{Q}{RT}\right)}{A} \right)^{\frac{2}{n}} + 1} \right\} \quad (8)$$

where, α , A , n are material parameters, Q surface activation energy of hot deformation, which is the important parameter reflected whether difficult or easy of thermal deformation, shown in Table 1, R the gas constant. The model parameters of hyperbolic sine constitutive equation of 5052 aluminum alloy were regressed from experimental data of Gleeble 1500 thermal simulation machine. Based on the plastic equations, the deformation flow stress should convert into deformation resistance as follows:

$$K = 1.15\sigma$$

3. Model Application

Through previous analysis and derivation, the elastic flatten roll radius, coefficient of stress state, deformation resistance model and the corresponding rolling force model concluded. According to equation (1) calculated the value of rolling force with the Matlab programming. Thereinto the flatten roll radius R' calculated through iteration of interim rolling force P according to the flow chart shown in Figure 1, and proceed to contact arc length l_c which taken roll elastic flattening into account.

The example of the above mentioned algorithm/program was applied to an actual rough hot rolling process, with a previous setting pass schedule of a thickness reduction from 550mm \rightarrow 7.2mm in 23 forwards and reverse passes for AA5052 aluminum alloy shown in Table 2, served in single stand hot rolling mill of some factory in China. The predicted curves calculated via the setting pass schedule, compared with actual measured one on-site, shown in Figure 2, (a) and (b) represent the 23rd and 22nd pass respectively, and (c) stands for the whole process from 1st to 23rd, can be confirmed accuracy of the model of rolling force.

Table 1. The hyperbolic-sine constitutive equation of hot deformation of aluminum alloys

alloy	n	Q (J·mol ⁻¹)	A	α
5052	8.222122	228236.03	1.79E+13	0.023322

Figures 2 and 3 show that, there was a preferable coincide between the calculated and measured values of rolling force, with calculation error of about 5% ~ 7% for vast majority pass of the process, except the previous 1st, 2nd and final pass in the process, shown in Figure 2 (c) and 3 (c), and unsteady state of biting and tail throwing of each pass, for example, the 23rd and 22nd passes, shown in Figure 2 (a),3(a) and 2(b),3(b), respectively, where singular value occurs. It demonstrated that the prediction accuracy for steady state is relatively high, fully meets the requirements of the actual production site. Obviously, the original schedule setting of rolling force had very large error sharp contrast to the actual measured. As the predicted was closer to the actual value of rolling force, the setting accuracy of rolling process parameters can be improved and consequently the accuracy of process control can be improved. It will help to improve precision of thickness, strip crown and shape accuracy.

Table 2. The pass schedule of thickness at entrance and exit of flat rolling

unit: mm												
pass no.	1st	2nd*	3rd	4th*	5th	6th*	7th	8th*	9th	10th*	11th	12th*
Entrance	550	535	520	495	470	440	410	380	350	320	290	255
Exit	535	520	495	470	440	410	380	350	320	290	255	225
pass no.	13th	14th*	15th	16th*	17th	18th*	19th	20th*	21st	22nd*	23rd	
Entrance	225	195	165	135	110	85	60	40	29	16	11	
Exit	195	165	135	110	85	60	40	29	16	11	7.2	

Remarks: * reversed pass .

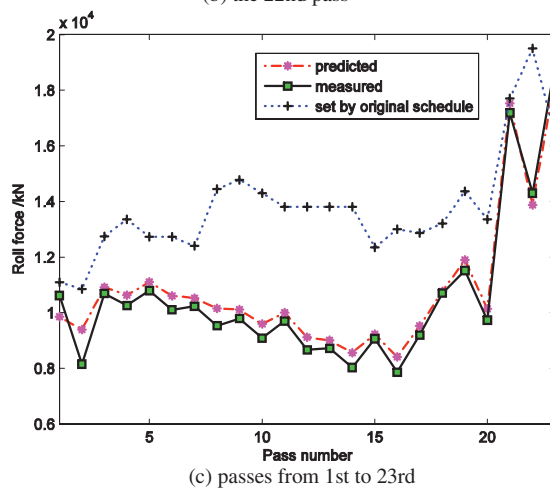
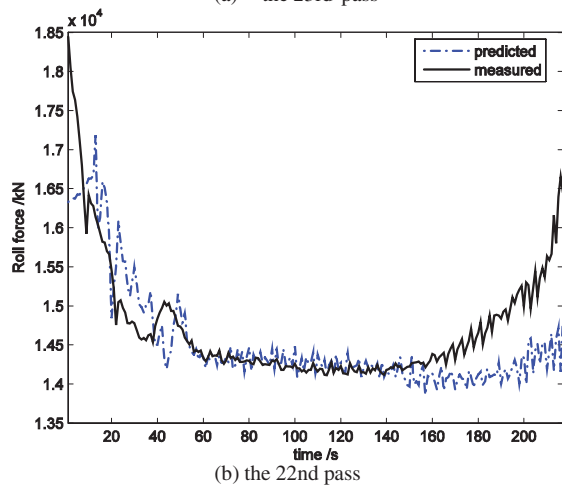
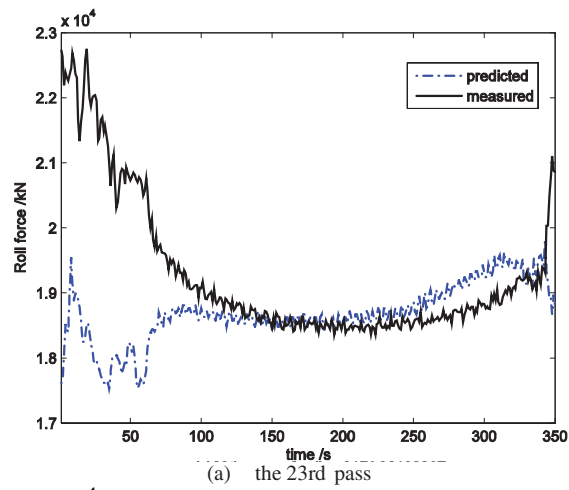
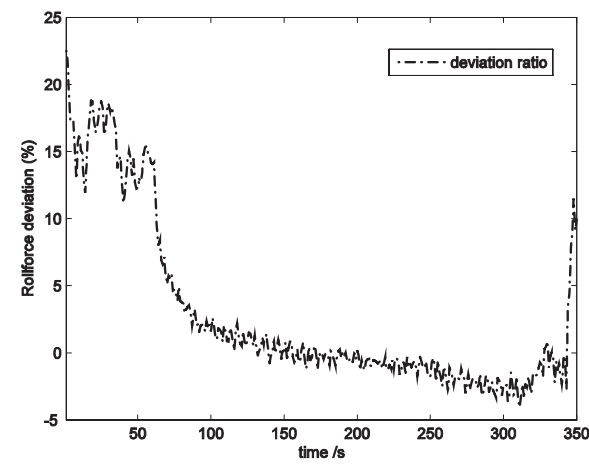
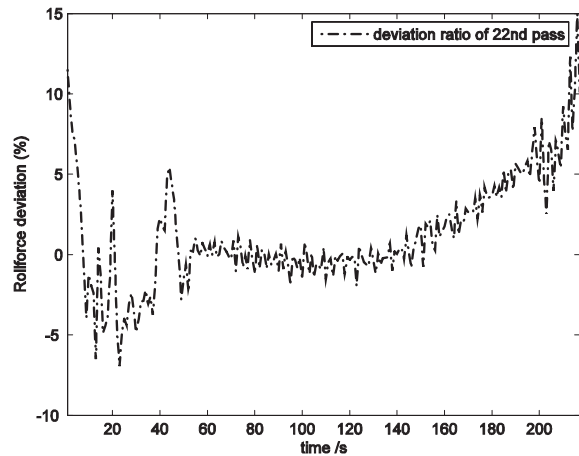


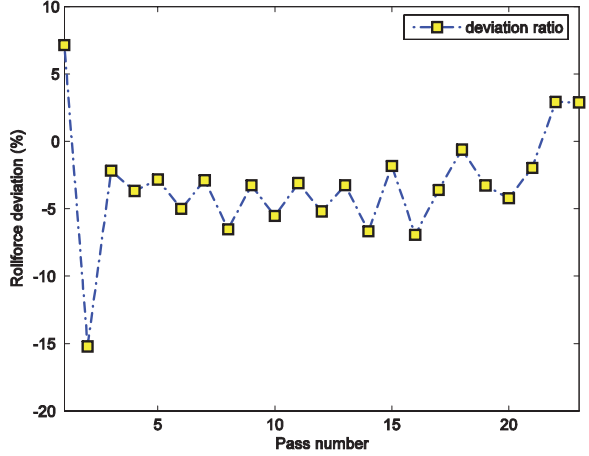
Fig.2 Comparison of rolling force predicted vs measured for AA5052 /23 passes (550mm→7.2mm)



(a) the 23rd pass



(b) the 22nd pass



(c) passes from 1st to 23rd

Fig.3 Prediction deviation of rolling force calculated vs measured for AA5052

The singular value of the previous 1st and 2nd pass of the rough rolling process was caused by both the thickness difference due to non uniform machining, for instance, actual ingot thickness was maybe 552mm or 547mm contrast to setting value 550mm of previous schedule, and temperature diversity due to different position in the furnace for the entrance ingot. The singular impact will decrease successively or eliminate in afterwards rolling process with generation and transformation of deformation heat and friction heat and in the wake of correspond of the size of gauge with setting schedule during rolling process. The singular value of final pass was due to variance of requested product specification, such as maybe 7.2mm or 7.5mm or 7.7mm, that means rolling schedule had changed a little contrast to setting value of previous schedule actually. This can be solved via self-learning process of control system, and it will, afterwards, further improve forecasting accuracy of rolling force at these singular points.

The singular value of unsteady state, or rather biting and tail throwing, of each pass, are very striking, obviously shown in Figure 2 and 3. It's very headache of accurate prediction of rolling force of unsteady state in the rolling process so far. The remarkable characteristic on these interim is that the rolling velocity is changed quickly and forward or backward tension are built or escalating or declining gradually.

4. Conclusion

The established model of rolling force calculation, based on the classic rolling theory and by means of three sub-models of the elastic flatten roll radius model, the stress state factor model and material deformation resistance model, was regressed based on actual production data and get high precision mathematical model. Compared the predicted values with the measured, it demonstrated that calculation results of rolling force by the mathematical model were in good agreement with the measured values.

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